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# Inflow characterization using measurements from the SpinnerLidar: the ScanFlow experiment

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**Abstract.** We present a preliminary analysis of inflow measurements performed with a SpinnerLidar on a turbine's nacelle and those from three grounded-based short-range continuous-wave lidars (WindScanners) during the ScanFlow experiment. After proper filtering for blade contamination and hub/nacelle shading of the beam, the SpinnerLidar measurements capture the structure of the inflow in detail. The WindScanners' 3D measurements provide estimations of the three wind speed components without any flow assumptions. These 3D wind field measurements are used as reference to evaluate SpinnerLidar reconstructed winds. A wind reconstruction methodology for the SpinnerLidar measurements is evaluated against a numerical wind inflow simulation successfully. An intercomparison between reconstructed longitudinal velocity components from the WindScanners and the Spinnerlidar shows good agreement (no bias and high correlation) at hub height and close to zero biases for all vertical levels measured by the SpinnerLidar.

## 1. Introduction

Forward-looking nacelle-mounted lidars have already been proven to be useful for power performance assessments [1], load validation [2], turbine control [3], and inflow turbulence characterization [4]. This is partly because their beams probe into the wind as the lidars are fixed on the turbine's nacelle. DTU developed a research lidar, the so-called SpinnerLidar [5], which can also be mounted on the hub/nacelle of a turbine and that can take measurements covering a large part of the turbine's rotor disk. It is therefore important to find out whether the SpinnerLidar measurements can improve the methods and outcomes of inflow characterization based on nacelle anemometry and thus improve the turbine's energy capture and load mitigation. The SpinnerLidar can also be used to characterize turbine wakes in detail [6].

The ScanFlow experiment aimed at investigating inflow characterization using measurements from two systems: a nacelle-based SpinnerLidar mounted on a turbine and the WindScanner (WS) system that consists of three short-range continuous-wave lidars (R2D1, R2D2, and R2D3). The experiment was conducted from December 2016 to February 2017 at ECN's test site of wind turbines in The Netherlands, which is a flat, agricultural terrain with scattered farm houses and trees. Only three days, 2017-01-29, 2017-02-04, and 2017-02-05, each of approx. 10 h are available for data intercomparison from a meteorological mast, the turbine, the SpinnerLidar, and the WS system. This is because the WS system was only operated during these periods in which the wind came from a direction that was thought to be less influenced by the turbines nearby. The WS measurements are here used as reference because the mast is not deployed



at the turbine inflow and because we can in principle derive the three wind-speed components directly from the WS system without any flow assumptions. The turbine is a Nordex N80 pitch-controlled machine with a rated power of 2.5 MW, and a rotor diameter and hub height of 80 m.

Figure 1 shows a top and a 3D view of the ScanFlow experiment that includes the WSs' locations and the scanned positions, and the turbine and the SpinnerLidar locations with an example of the scanning pattern. Since the idea was to compare the WSs' retrievals with those of the SpinnerLidar, the WSs were deployed such that R2D1 was upstream from the focus distance of the SpinnerLidar, which was set to 71.6 m at an angle of 235 deg from the north. This angle allows us to have close to undisturbed wind conditions and secures data due to the predominant southwesterlies. The other two WSs were deployed on each side of the 235 deg line between the turbine and the upstream unit. Each of the WSs was intended to measure on a vertical line (see Fig. 1-bottom) 'covering' the SpinnerLidar measurements. Based on forecasts of the wind direction and maximized scan speed, the WSs did not measure over the 235 deg line from the turbine but over a 215 deg line.

## 2. SpinnerLidar

The SpinnerLidar is a continuous-wave wind lidar that scans in a rose-curve pattern (see Fig. 1-bottom). A typical 2D rotor plane rosette (1 full scan) generates  $\approx 488$  radial velocities; the instrument was setup to perform 60 rosettes per minute. Since the SpinnerLidar was mounted on top of the nacelle behind the rotor, the data needs to be filtered because of blade contamination, among others. We follow the method by [7] in which all possible blade returns are simulated and excluded from the data. The simulated radial velocity of the blade is expressed as

$$v_r = |\Omega S_x h_l|, \quad (1)$$

where  $\Omega$  is the rotor angular speed,  $S_x$  the projection of the unit vector along the radial measurements on the  $x$  direction, and  $h_l$  is the distance of the lidar from the hub center. We also filter out all radial velocities below  $3 \text{ m s}^{-1}$ . Spurious radial velocities from bore point optical reflections near the centre of the rosette and other noise sources might remain in the data and so we include a criterion regarding signals with low power and filter out spikes using the method by [8]. A typical 1-min SpinnerLidar scan is shown in Fig. 2. After filtering, a 1-min period typically contains only about half the original amount of scans. It is seen that the filtering removes measurements within the bottom region of the scan because the beam hits the hub/nacelle. The radial velocity contours also show, for this particular example, that the turbine is not following perfectly the wind as higher values are concentrated to the right of the scanning pattern.

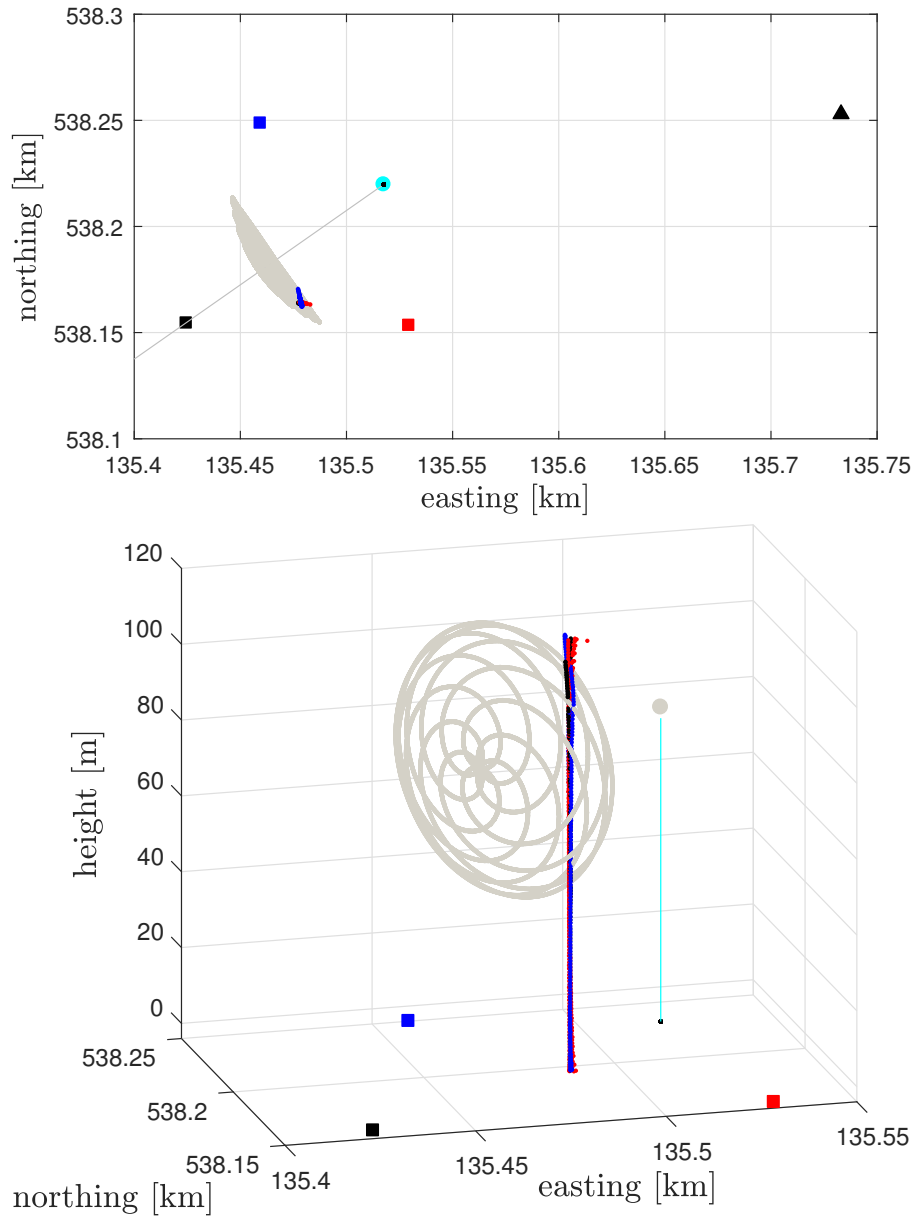
### 2.1. Wind-speed reconstruction

We employ a simple method to reconstruct the wind field. A rectangular grid with a  $2 \text{ m} \times 2 \text{ m}$  resolution is adjusted to the positions scanned by the SpinnerLidar on the  $x$ - $y$  plane as shown in Fig. 3. Since we know the positions of the beam in this plane, we can compute the radial velocities at each of the positions in the rectangular grid by, e.g., linear interpolation. In Fig. 3, we show simulated radial velocities at the positions in the grid from a simulated wind field with a hub-height longitudinal velocity of  $10 \text{ m s}^{-1}$ , a shear exponent of 0.2 (between the highest and lowest vertical levels), with  $v = w = 0 \text{ m s}^{-1}$ , being the  $v$  and  $w$  the cross-wind and vertical velocities, yawed 0 and 20 deg. We assume zero cross-wind and vertical velocities because the reconstruction will be performed based on 10-min averages.

The 'yawed' unit vector of the pointing SpinnerLidar beam can be expressed as

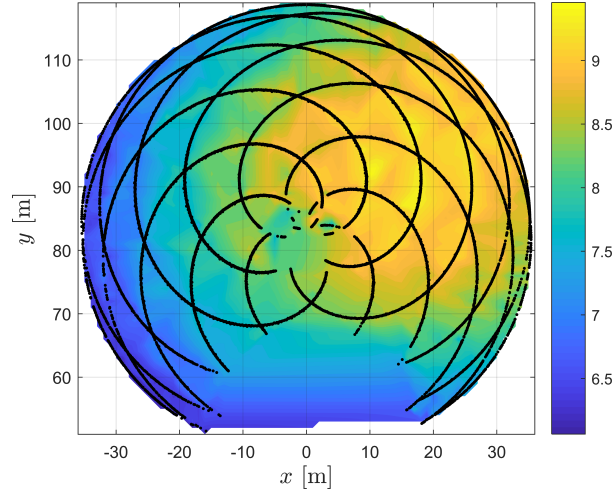
$$\mathbf{n}(\beta) = (-\cos \varphi \cos \beta + \sin \varphi \cos \theta \sin \beta, \cos \varphi \sin \beta + \sin \varphi \cos \theta \cos \beta, \sin \varphi \sin \theta), \quad (2)$$



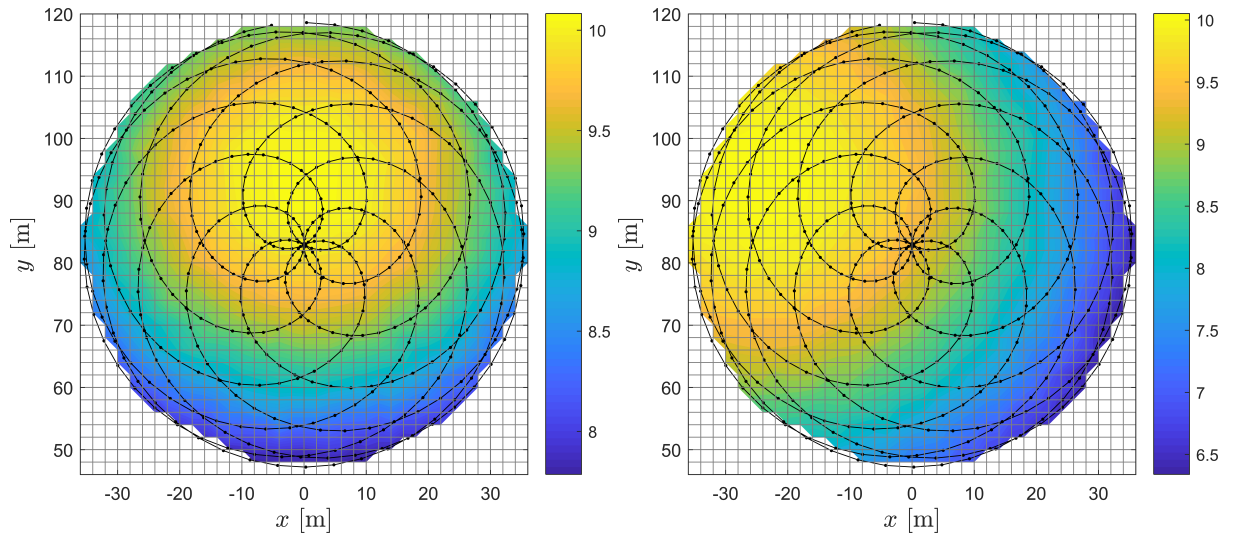


**Figure 1.** (Top) top view of the ScanFlow experiment. WindScanners are shown in red, black and blue squares, their measurements in dots with the same colors, the turbine in cyan, the SpinnerLidar measurements in grey, and a WindCube in the black triangle. (Bottom) a 3D view of the experiment

where  $\beta$  is the yaw misalignment,  $\varphi$  the angle between the beam and the  $z$ -axis, and  $\theta$  the angle between the  $x$ -axis and  $\mathbf{n}$  projected onto the  $x$ - $y$  plane. By definition, the radial velocity is  $v_r = \mathbf{n} \cdot \mathbf{u}$ , where  $v_r$  is the radial velocity and  $\mathbf{u} = (u, v, w)$  the wind vector with  $u$  aligned with the  $z$ -axis,  $v$  with the  $x$ -axis, and  $w$  with the  $y$ -axis. We can therefore estimate both  $u$  and  $\beta$  (assuming  $v$  and  $w$  are zero as explained above) for each vertical level of the grid, using the radial velocity and beam geometry information of all horizontal grid cells within the vertical level, i.e., assuming that both  $u$  and  $\beta$  are horizontally constant and varying only with height. We call this method estimate 1.



**Figure 2.** Upward looking front view of a typical 1-min SpinnerLidar scan during the ScanFlow experiment. Colors represent the radial velocity in  $\text{m s}^{-1}$  and black markers the beams' positions after filtering



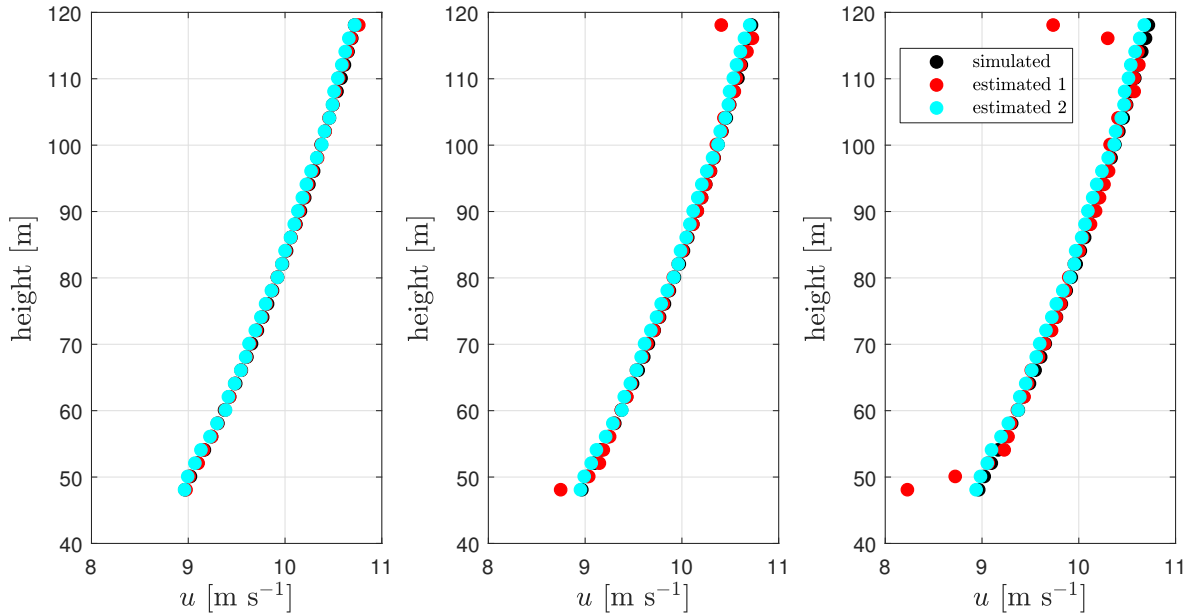
**Figure 3.** Simulated radial velocities computed on the SpinnerLidar positions based on a simulated sheared flow yawed 0 deg (left) and 20 deg (right). Colors represent the radial velocity in  $\text{m s}^{-1}$ , black markers the beam's positions, and in grey lines the rectangular grid

Due to the scanning pattern of the SpinnerLidar, we have enough radial velocity information to estimate both  $u$  and  $\beta$  at hub height because at that vertical level, the beams 'open' about 30 deg from the vertical axis. However, the beams 'narrow' when going higher or lower and so the uncertainty in the estimated  $u$  and  $\beta$  values highly increases. Therefore, we have another estimate of  $u$  that assumes a constant yaw (the value estimated at hub height  $\beta_{hh}$ ):

$$u = v_r / (\cos \varphi \cos \beta_{hh} - \sin \varphi \cos \theta \sin \beta_{hh}). \quad (3)$$

We call this method estimate 2. Figure 4 shows the results of the reconstruction of the  $u$  component for three different yaw scenarios (same simulated wind field). It is clearly seen that as the yaw increases the bias in the reconstruction for estimate 1 increases too and the positions

most affected are those further from the hub height.



**Figure 4.** Simulated and reconstructed longitudinal velocity component of the wind speed with height for three yaw misalignment scenarios: 10 deg (left frame), 20 deg (middle frame), and 30 deg (right frame)

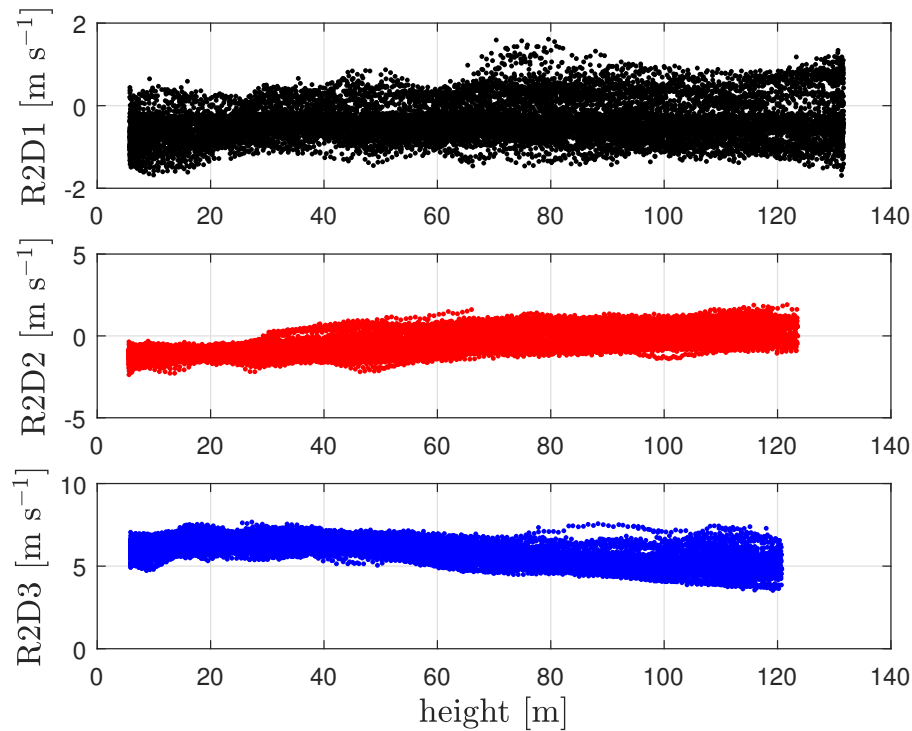
### 3. WindScanners

Figure 1-right shows that the WSs intended to scan on a virtual vertical line from  $\approx 6$  to 130 m. The virtual line was scanned continuously with the WSs and they took about 0.5 s to go from top to bottom. The radial velocities are estimated at a rate of about 333 Hz. Due to mechanical reasons, some scanned positions drifted away from the virtual line. Therefore, we filter out scans when the difference between the scanned distance and the ideal position in the virtual line was larger than 2 m. An example of the WSs' radial velocities for a 1-min period during the ScanFlow experiment is shown in Fig. 5. The wind direction for this period is about 180 deg and due to the locations of the systems, R2D1 and R2D2, which are to the sides of the virtual line, show values close to 0, while R2D3, north of the virtual line, shows the highest radial velocities, as expected.

#### 3.1. Wind-speed reconstruction

We reconstruct the velocity components by gridding the radial velocities and the scanned positions within 1-m vertical cells from 6 up to 118 m for each of the lidars separately. For each vertical cell, a linear system,  $[v_{rR2D1}, v_{rR2D2}, v_{rR2D3}] = M[u, v, w]$ , where  $M$  is a matrix with the cosines of the 9 angles between the unitary velocity vectors and the vectors between the WindScanners and the scanned point positions, is used to compute the  $u$ -,  $v$ -, and  $w$ -components.

Figure 6 shows an example of the estimated velocity components as function of height, and of the horizontal wind-speed magnitude  $U$ , for the same 1-min period of Fig. 5. Here  $u$  and  $v$  are on a coordinate system pointing eastwards and northwards, respectively. Therefore,  $u$  is close to zero and  $v$  shows the highest values (the direction is about 180 deg). As shown, we estimate



**Figure 5.** Example of the behavior of the WindScanners' radial velocities with height for a 1-min period

$w$  from 20 m since the elevation angles below that height are too small and the uncertainty in the  $w$ -component estimation dramatically increases.

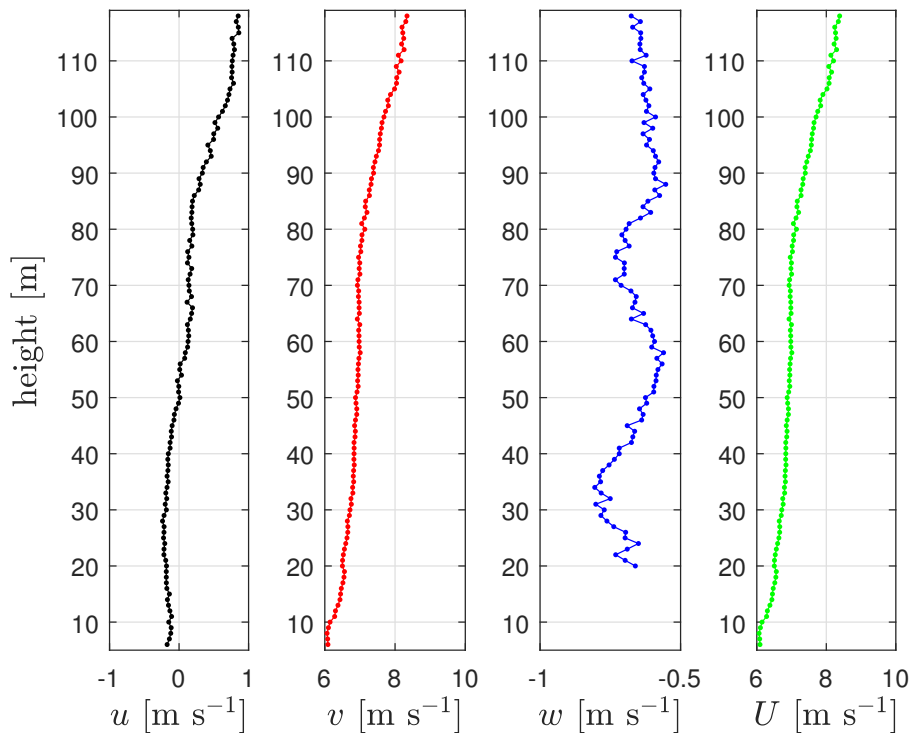
#### 4. Wind and turbine-operating conditions

Figure 7 shows the wind conditions (1-min averages) of the three periods based on the observations from a cup anemometer and a vane at 80 m on the closest mast, the turbine (nacelle wind speed and direction), and the WS system (reconstructed winds at hub height). The first period shows high variability both in terms of wind speed and direction, while during the second period the wind is much less variable. During the third period, the wind speed is most of times below the cut-in value.

From a comparison between the yaw signal of the turbine and the nacelle wind direction for 1-min averages (not shown), it is seen that for the two first periods, when the wind speeds are above the cut-in value, the turbine closely follows the wind, whereas for the third period the turbine generally stops yawing due to low wind-speed conditions. Since the idea is to compare the SpinnerLidar retrievals with those of the WS, we will use the first two periods because the SpinnerLidar retrievals are based on the frame of reference of the turbine.

#### 5. Results

We have 408 and 179 10-min periods of reconstructed winds from the SpinnerLidar and WSs, respectively, during the three above mentioned days. Of those, 177 10-min periods are available of concurrent WSs-Spinnerlidar reconstructed winds. Figure 8-left shows a comparison of the reconstructed  $u$ -velocity component at hub height from the SpinnerLidar and the WSs' radial velocity measurements. Since we need to rotate the WSs' reconstructed winds to the frame of reference of the SpinnerLidar, i.e., that of the turbine, we need to apply filters regarding both



**Figure 6.** Example of the estimated wind velocity components from the WindScanners' radial velocities as function of height for a 1-min period

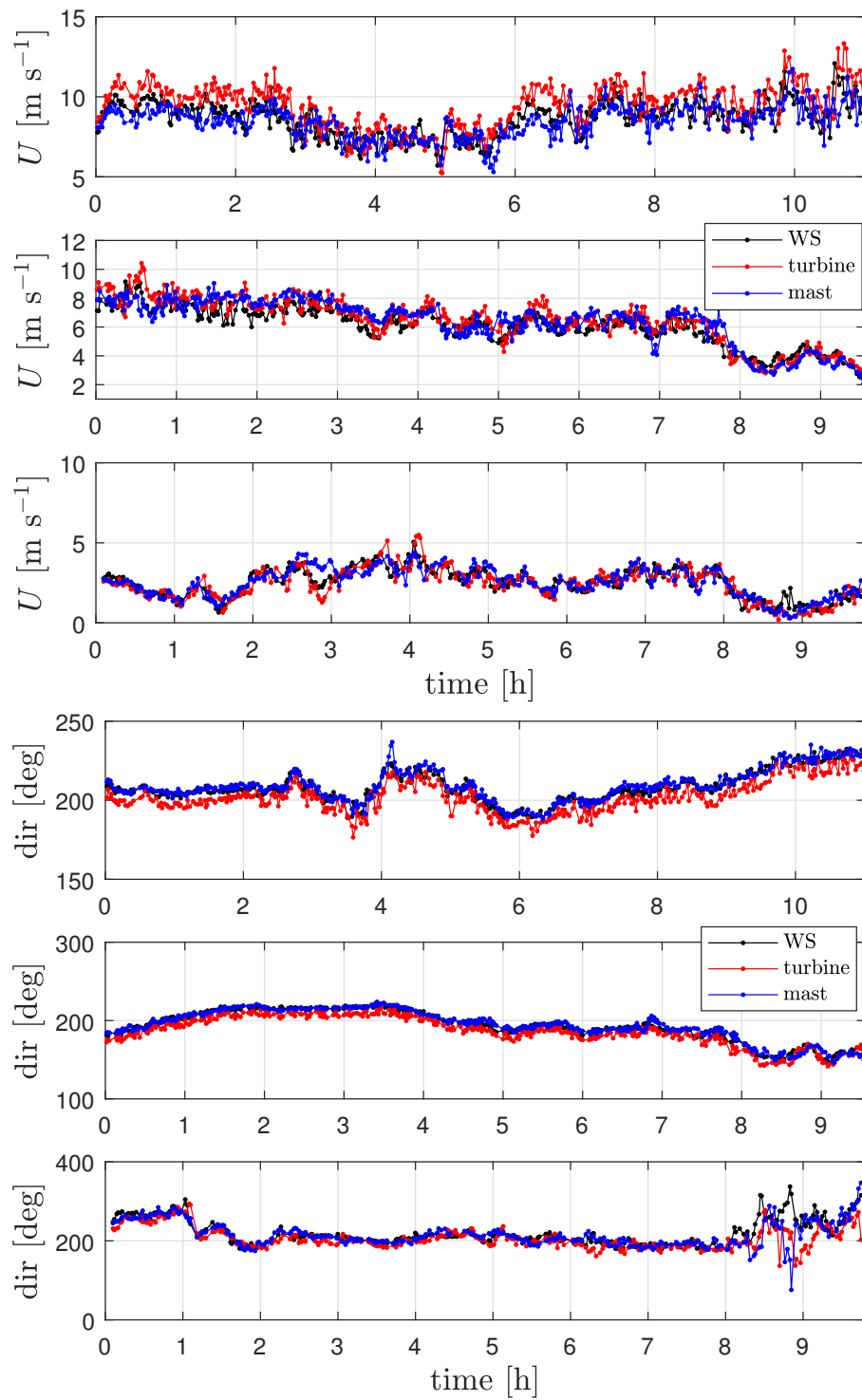
the operational status of the turbine and a minimum wind speed threshold that ensure a yawing turbine. Further, we select 10-min periods with a minimum of 100 radial velocities for each of the WSs at the hub-height grid cell and a minimum of 1000 SpinnerLidar radial velocities at the horizontal cells at hub-height.

The  $u$ -velocity component derived from the WSs' measurements seems to be in good agreement with that derived from the SpinnerLidar measurements (0% bias) and there is some scatter (coefficient of determination  $R^2$  of 0.95), which is typically higher to that found from lidar intercomparison studies [9]. The WSs' reconstructed wind speeds need to be rotated for the comparison with the SpinnerLidar derived winds. We use the nacelle signal of the turbine for this purpose but this is discretized as the turbine does not follow the turbine smoothly and continuously, which explains part of the scatter. It is also possible that one or both of the reconstructed winds are not accurate enough. Hardening the filtering criteria with regards to the number of points available for reconstruction for both the SpinnerLidar and WSs measurements increases the correlation between reconstructed winds only slightly with the expense of reducing the amount of data.

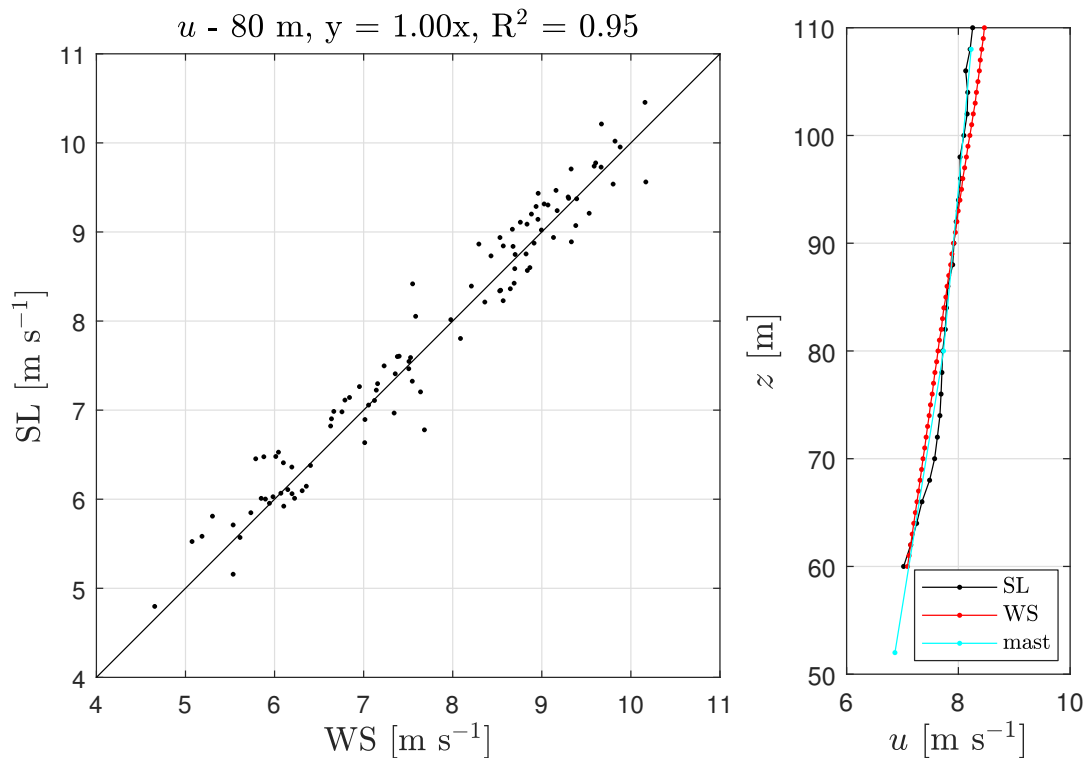
Figure 8-right shows an intercomparison of the average vertical profile of the  $u$ -velocity component derived from the mast, WSs, and SpinnerLidar measurements. All three profiles have similar behavior; the WSs' profile showing slightly higher values within the upper part of the profile and the SL's profile within the lower part of the profile.

## 6. Conclusions

A simple method to estimate winds from SpinnerLidar measurements was presented and evaluated against numerical simulations of the wind field. The agreement between simulations and the reconstructed values of the longitudinal velocity component is very good for a number



**Figure 7.** 1-min averages of wind speed (top) and direction (bottom) of the three periods (top, middle and bottom) based on measurements from the mast, turbine and WindScanners (WS)



**Figure 8.** (Left) comparison of the reconstructed  $u$ -velocity component at hub height from the SpinnerLidar and the WindScanner system measurements. (Right) comparison of the vertical profiles of the  $u$ -velocity component from the mast, WindScanner system, and SpinnerLidar measurements

of yawing scenarios. The method is tested using measurements from the ScanFlow experiment where reference measurements from a 3D WindScanner system are available. It was also found good agreement between the reconstructed longitudinal velocity component from the WindScanner system and that from the SpinnerLidar measurements for a wide range of vertical levels (60–110 m) on a 10-min basis. The intercomparison shows some scatter that might be due to the turbine yaw signal, which is needed to rotate the WS-based reconstructed wind speed to the SpinnerLidar's frame of reference.

## 7. Future work

Future work will be on further intercomparisons of the reconstructed wind speeds between the different systems, including measurements from a WindCube profiler deployed close to the WS system. Different methodologies for estimating turbulence parameters from the SpinnerLidar measurements will also be evaluated against turbulence estimations from the other systems.

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